Electrochromic Windows for Commercial Buildings: Monitored Results from a Full-Scale Testbed

Eleanor S. Lee, Dennis L. DiBartolomeo, and Stephen E. Selkowitz
Lawrence Berkeley National Laboratory

ABSTRACT

Electrochromic glazings promise to be the next major advance in energy-efficient window technology, helping to transform windows and skylights from an energy liability to an energy source for the nation's building stock. Monitored results from a full-scale demonstration of large-area electrochromic windows are given. The test consisted of two side-by-side, 3.7x4.6-m, office-like rooms. In each room, five 62x173-cm lower electrochromic windows and five 62x43-cm upper electrochromic windows formed a large window wall. The window-to-exterior-wall ratio (WWR) was 0.40. The southeast-facing electrochromic windows had an overall visible transmittance (T_v) range of T_v=0.11-0.38 and were integrated with a dimmable electric lighting system to provide constant work plane illuminance and to control direct sun.

Daily lighting use from the automated electrochromic window system decreased by 6 to 24% compared to energy use with static, low-transmission (T_v=0.11), unshaded windows in overcast to clear sky winter conditions in Oakland, California. Daily lighting energy use increased as much as 13% compared to lighting energy use with static windows that had T_v=0.38. Even when lighting energy savings were not obtainable, the visual environment produced by the electrochromic windows, indicated by well-controlled window and room luminance levels, was significantly improved for computer-type tasks throughout the day compared to the visual environment with unshaded 38%-glazing. Cooling loads were not measured, but previous building energy simulations indicate that additional savings could be achieved. To ensure visual and thermal comfort, electrochromics require occasional use of interior or exterior shading systems when direct sun is present. Other recommendations to improve electrochromic materials and controls are noted along with some architectural constraints.

Introduction

Electrochromic glazings promise to be the next major advance in energy-efficient window technology, helping to transform windows and skylights from an energy liability to an energy source for the nation's building stock. Electrochromic glazing can be reversibly switched from a clear to a transparent, colored state by means of a small applied voltage, resulting in thermal and optical properties that can be dynamically controlled. "Smart windows" incorporating electrochromic glazings could reduce peak electric loads by 20 to 30% in many commercial buildings and provide added daylighting benefits throughout the U.S., as well as improve comfort and enhance productivity in our homes and offices. These technologies will provide maximum flexibility in aggressively managing energy use in buildings in the emerging deregulated utility environment and will move the building community toward the goal of producing advanced buildings that have minimal impact on the nation's energy resources. Customer choice will be further enhanced by the flexibility to dynamically control envelope-driven cooling and lighting loads.

Large-area electrochromic windows have very recently become available in limited quantities. Samples of these windows were installed in two side-by-side private office test rooms, enabling researchers to conduct full-scale monitored tests. Full-scale tests bring bench top laboratory designs one step closer to commercialization by solving key design issues in a realistic building environment with a short test-evaluate-test iterative cycle of development. We present performance data from the nation's first demonstration of this advanced large-area switchable glazing. These research results will help electrochromic developers improve their product designs and offer other stakeholders, such as utilities, building owners, and consumers, an informed understanding of the in-situ performance benefits of this emerging technology.

Background

An electrochromic device consists of a purely ionic conductor (electrolyte) that is placed between an electrochromic layer and a counter electrode, which is, in turn, placed between transparent electrical conductors. When voltage is applied to the transparent conductors, an electrochemical reaction occurs in which ions are inserted or extracted from the electrochromic layer, resulting in a modulation of optical properties (Granqvist 1999). The electrochemical effect was first explained by Deb (1969); since then, substantial research has been dedicated to developing viable thin-film coatings for large-area windows and other applications.

During the early 1980s, electrochromic coatings on small-area samples (~2x2 cm) were developed and characterized in laboratories, with emphasis on optimizing material properties and creating consistent production techniques for optical displays and watches. Interest waned by the mid-1980s when it was recognized that electrochromics could not compete with liquid crystal displays in response time. During the early-1990s, electrochromics were recognized as having advantages for use in buildings and rear-view mirrors in automobiles; renewed research and development focused on new aspects of electrochromic devices for window-specific applications, e.g., characterizing counter electrodes and incorporating contributions from other fields for highly-conducting polymer electrolytes (Scrosati 1996). Essential electrochromic performance parameters for building applications have been described in the materials science literature (Czanderna et al. 1999) as follows:

- continuous range in solar and optical transmittance, reflectance, and absorptance in bleached and colored states
- contrast ratio (CR) of at least 5:1 (maximum T: minimum T)
- coloring and bleaching times (switching speed) of a few minutes
- operating temperatures of –20°C to 80°C
- switching with applied voltages of 1-5 V
- open circuit memory of a few hours (maintains a set state of transmission without corrective voltage pulses)
- acceptable color
- large area with excellent optical clarity
- sustained performance over 20-30 years
- acceptable cost of $\$100/m^2$

At this time, large-area (90x200-cm) electrochromic windows can be produced in small quantities at substantial cost ($\sim\$1000/m^2$). Volume production facilities are being developed. Developers expect electrochromic window products to emerge in the marketplace by the years

2001-2002. With volume production, electrochromic window costs are expected to drop to about \$100/m^2, not including control electronics. Materials performance, optical characterization, coloration efficiency, durability, and fabrication techniques continue to be major research and development issues.

Research is currently being conducted to determine how large-area electrochromic windows will perform in buildings. The Electrochromic Initiative, launched in 1994 by the U.S. Department of Energy (DOE), has supported materials technical support and durability testing by industry teams in collaboration with DOE national laboratories. Task 27, "Building Envelope Components," of the International Energy Agency (IEA) Solar Heating and Cooling Programme/ Energy Conservation in Building and Community Systems, began in January 2000 to determine the solar, visual, and thermal performance of advanced windows, including electrochromic glazings. This activity, with participation of 18 countries around the world, will include test cell experiments as well as characterization of large-area windows and definition of test protocols.

Full-scale tests are essential to understanding how electrochromic windows will perform in real buildings. Unlike many energy-efficient glazing technologies, electrochromic glazings have *size-dependent* characteristics. The switching speed of a 1x2 device will be faster than that of a 2x4 device. The optical range and contrast ratio are expected to remain the same with size; however, this has yet to be verified for the full array of devices developed in laboratories. An electrochromic device will switch significantly more slowly when cold than when hot. An automated, integrated window-lighting control system is needed to realize lighting and cooling energy savings. Few electrochromic prototypes have been produced in the large sizes required by the building industry, so few performance studies of them have been conducted.

Detailed market assessments have been conducted by industry, but this information remains proprietary. Electrochromic developers are under increased pressure to provide compelling evidence that can justify the large financial investments necessary for engineering development and fabrication facilities. As has been noted in our earlier work, the economic equation for electrochromics has not been a simple engineering optimization problem but instead a problem that must include energy and peak demand costs; heating and cooling system sizing; environmental impacts; thermal and visual comfort; privacy; aesthetics; and design, maintenance, and operation costs. Tradeoffs between energy savings and occupant satisfaction are difficult to codify. Yet typical market and technology assessments apply conventional life-cycle cost analysis methods to determine the viability of electrochromic windows. Some stakeholders perceive the cost, information, and operational barriers to be significant, concluding that electrochromics are not worthy of short-term investments until these issues have been resolved. However, electrochromics require a fundamental change in our perception of the design and function of the building envelope: a once passive building element has been transformed into an active element that can participate in whole-building integration activities, which impact building as well as human performance.

Method

Large-area electrochromic windows were installed in two side-by-side test rooms in the Oakland Federal Building, Oakland, California, and operated from November 1999 through

Figure 1. Interior view of test room B on a partly cloudy day, February 23, 2000. The electrochromic windows are in the clear state at 10:30 under diffuse light conditions (left). When sun enters the window, the electrochromic switches to its fully colored state by 10:50 (right).

February 2000. Test objectives included control system development, energy monitoring, and visual comfort evaluation. Detailed technical reports on the tests will be published elsewhere. Each test room was 3.71 m wide by 4.57 m deep by 2.68 m high and furnished with nearly identical building materials, furniture, and mechanical systems to imitate a commercial office environment (Figure 1). The southeast-facing windows in each room were simultaneously exposed to approximately the same interior and exterior environments so that measurements between the two rooms could be compared.

A laminated electrochromic glazing was combined with a low-emittance (low-E) glazing to form an insulating-glass unit (IGU) with a visible transmission (Tv) range of Tv=0.14-0.51 and a Tv contrast ratio of 1:3.6. Each electrochromic IGU was placed interior to the building's existing monolithic green-tinted glazing (Tv=0.75). The resulting composite visible transmission range was Tv=0.11-0.38. The electrochromic IGUs were placed in an array of five upper (62.1x43.2 cm) and five lower (62.1x172.6 cm) windows to cover the full area of the window opening (3.71 m wide by 2.29 m high). The window-to-exterior-wall ratio (WWR) was 0.40. The windows were not shaded by exterior or interior devices, but there were significant horizon obstructions from nearby buildings (25˚ average altitude). The five upper electrochromic windows could be controlled as a group independently from the five lower electrochromic windows, and all were switched with a voltage between 0-3 V. The windows had an open circuit memory and required no corrective voltage pulses to maintain a fixed transmission state. Two pendant indirect-direct (~95%, 5%) fixtures with four T8 32-W lamps, continuous dimmable electronic ballasts, and a shielded photosensor were used in each room. The ballasts were rated to produce 10% light output at a minimum power input of 33%. Lighting power density was 14.53 W/m^2.

The prototype system was defined by automated, switched electrochromic windows integrated with the dimmable fluorescent lighting system to maintain an interior work plane illuminance of 510 lux throughout the day. This case will be referred to in the text as "EC-glazing." This control strategy was designed to offset electric lighting use while minimizing solar heat gain loads on the cooling system. This strategy has been shown to yield the least annual building energy use for cooling-load-dominated commercial office buildings (Sullivan et al. 1994). However, the electrochromics were also switched to their fully colored, minimum transmission state to control direct sun. This added strategy will decrease total energy savings.

The base-case systems were defined by static, unshaded electrochromic windows—either fully bleached or fully colored all day—and the same dimmable fluorescent lighting system as the prototype system. These cases will be referred to in the text as “11%-glazing” or “38%-glazing.” The base case does not represent all characteristics of typical buildings because interior and exterior shading systems are generally used during some part of the day. However, manually deployed shading systems were not monitored in this experiment.

Electric lighting power consumption was measured in each test room with watt transducers (Ohio Semitronics GW5) that were accurate to 0.2% of reading. Daily lighting energy use was defined as the sum of data sampled every 6 minutes over a 12-hour period, from 6:00 to 18:00. Daily lighting energy use between rooms, under identical conditions, was found to correlate to within -103±6 Wh (4.0%±0.5%, n=2). Cooling load monitoring was not conducted as the data would not be meaningful for the electrochromic IGU positioned on the interior of the existing window.

Weather data, collected on a nearby roof, were sampled and recorded every 1 minute by a CR10 datalogger. Interior illuminance and electrochromics data were sampled and recorded every minute from 5:00 to 19:00 by a National Instruments LabView data- acquisition system. Horizontal illuminance was measured at a work plane height of 0.76 m in a two by five array of Li-Cor sensors. Window luminance data were collected with a shielded Li-Cor sensor placed on the rear wall of the test room facing the window. A separate vertical illuminance sensor array was placed 2.3 m from the window at a seated eye level height of 1.22 m in the center of the room facing either side wall and the window. The glare subjective rating (Osterhaus and Bailey 1992) was computed from the vertical illuminance data and is a measure of discomfort glare caused by viewing high or non-uniform luminance when performing computer visual-display terminal (VDT) tasks. A value of 0.5 defines the borderline between “just imperceptible” and “just noticeable,” 1.5 defines the borderline between “just noticeable” and “just disturbing,” and 2.5 defines the borderline between “just disturbing” and “just intolerable.”

Results

Winter data for typical clear, partly cloudy, and overcast skies are presented in three ways (Figures 2-6):

(a) Electrochromic operation is shown with the average T_v of the ten electrochromic windows as they switch in response to outdoor solar conditions. The exterior global horizontal illuminance (E_{vgh}), measured on the roof of an adjacent building, gives an indication of exterior solar conditions. Note that exterior obstructions for E_{vgh} differ from those for the vertical windows of the test rooms. Under overcast skies (Figure 6), note also that the EC-glazing does not cycle but remains in a full bleached state throughout the day. Therefore, comparisons between the automated electrochromic and the 38%-glazing (bleached) base case are not given.

(b) Control validation is given by average total (daylight and electric light) work plane illuminance data measured by four sensors located 2.44 and 3.35 m from the window wall and ±0.74 m from the centerline of the window, and average predicted fluorescent lighting work plane illuminance for the same location (determined by a correlation of power to measured illuminance (r^2=0.97). This gives an indication of how well the control system was able to meet

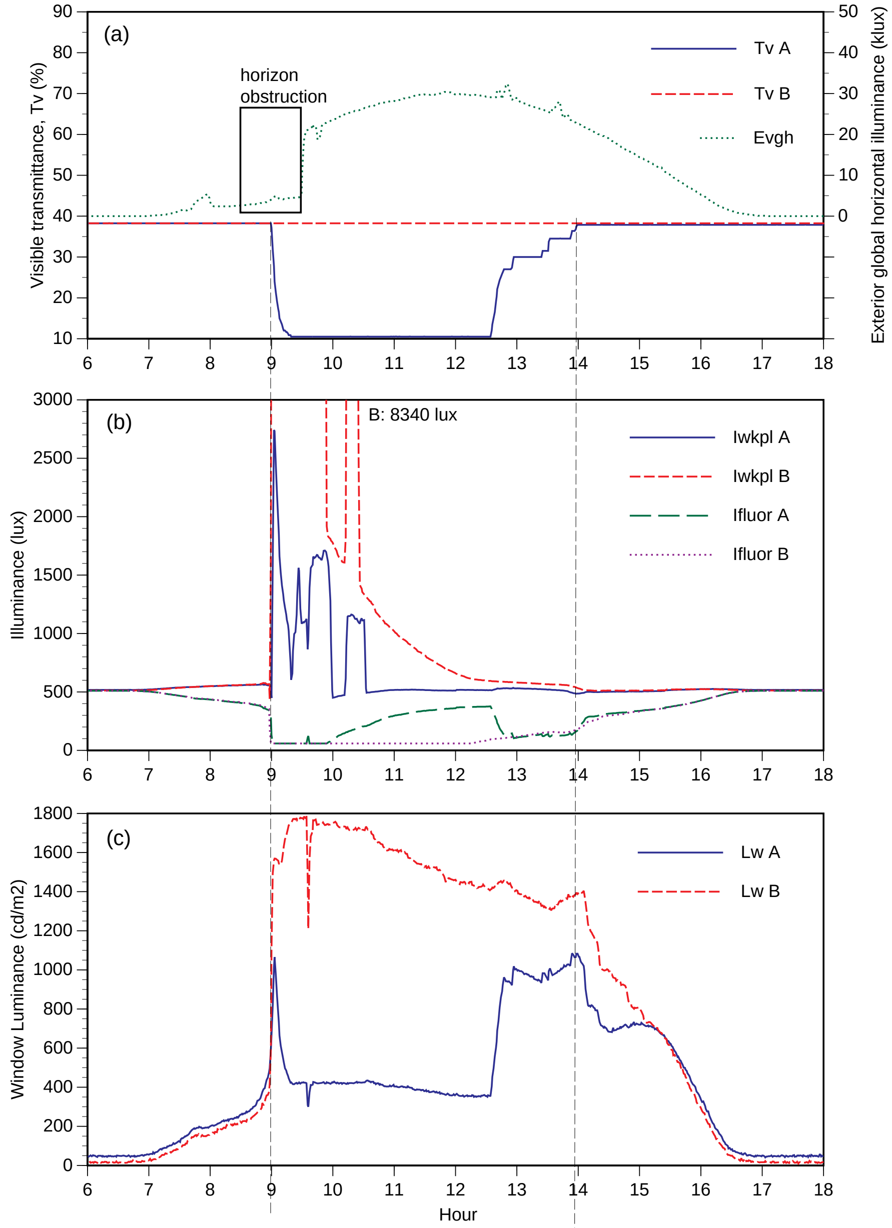

Figure 2. Clear sky, December 11, 1999
Room A: automated electrochromic; Room B: 38%-glazing

illuminance control objectives and of the brightness in the rear portion of the room. For graphs that clip the data, the maximum value is indicated in text on the figure.

(c) Visual comfort data are given by the average luminance of the window and the discomfort glare subjective rating (SR) for a view facing the window (worst case) located 2.3 m from the window in the center of the room. SR data are not available for clear sky conditions (Figures 2 and 3). Summary data for representative winter days are given in Tables 1-2.

An example interpretation of the data for the clear sunny winter day of December 11, 1999 (Figure 2) is provided. The electrochromic window is switched from full bleached to full colored when direct sun enters the window in the morning. It remains in this state until mid-day, after which it is gradually switched to the full bleached state as the sun moves out of the win-

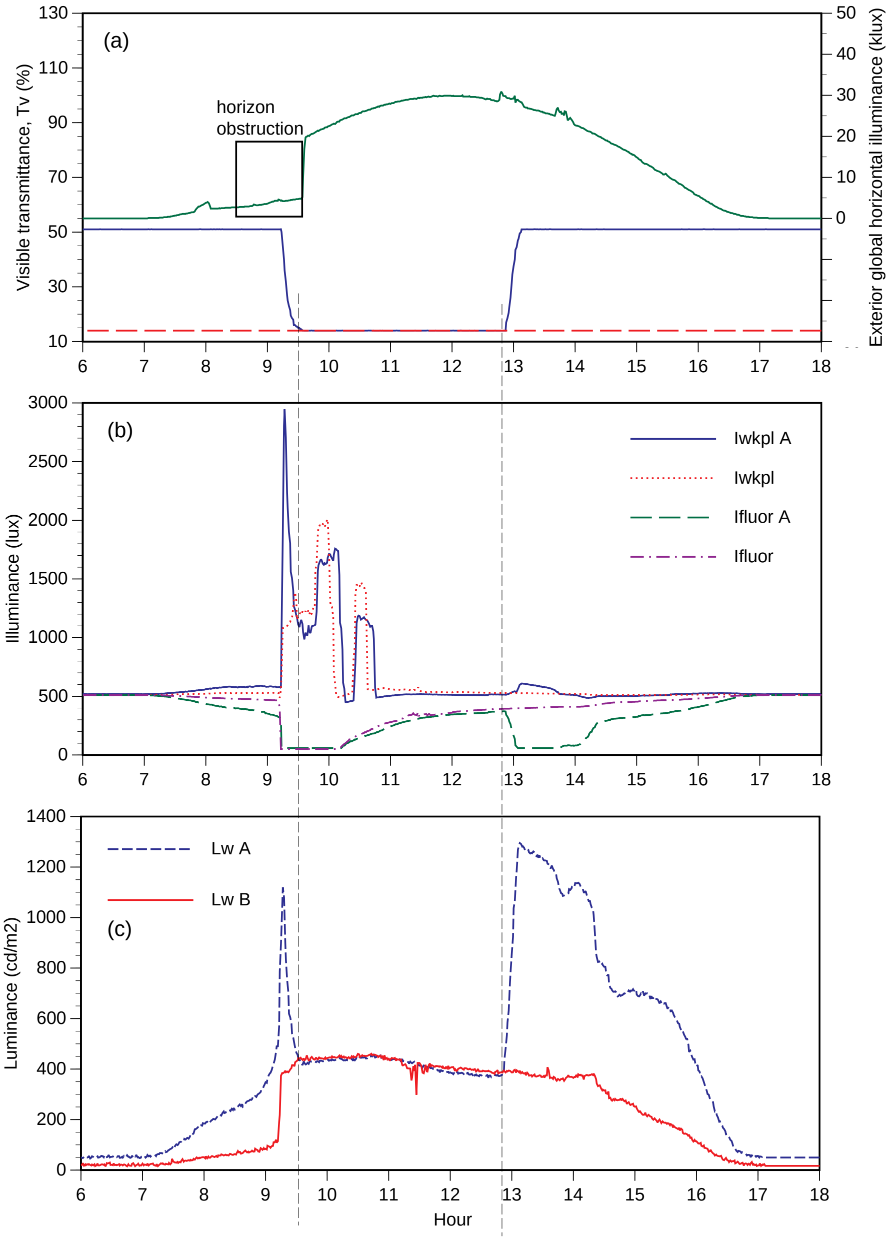

Figure 3. Clear sky, December 20, 1999
Room A: automated electrochromic; Room B: 11%-glazing

dow plane for the rest of the day. Fluorescent lighting is used in the early morning, mid-morning, and late afternoon; the mid-morning lighting use is a compensation for direct sun control even though more than sufficient daylight is available. Work plane illuminance throughout the entire room peaks at 8,110 lux under direct sun, and the average rear-area illuminance peaks at 2,741 lux. Average window luminance is controlled in the morning to within ~400 cd/m^2 after the electrochromic windows first switch from bleached to colored (with 20-minute delay because of switching speed), then rises to less acceptable brightness levels in the early afternoon—850-1,080 cd/m^2 from 12:44 to 14:08—as direct sun control restrictions are relaxed. The window luminance exceeds the IES RP-1 (1993) limit of 850 cd/m^2 for 89 minutes or 12% of the day.

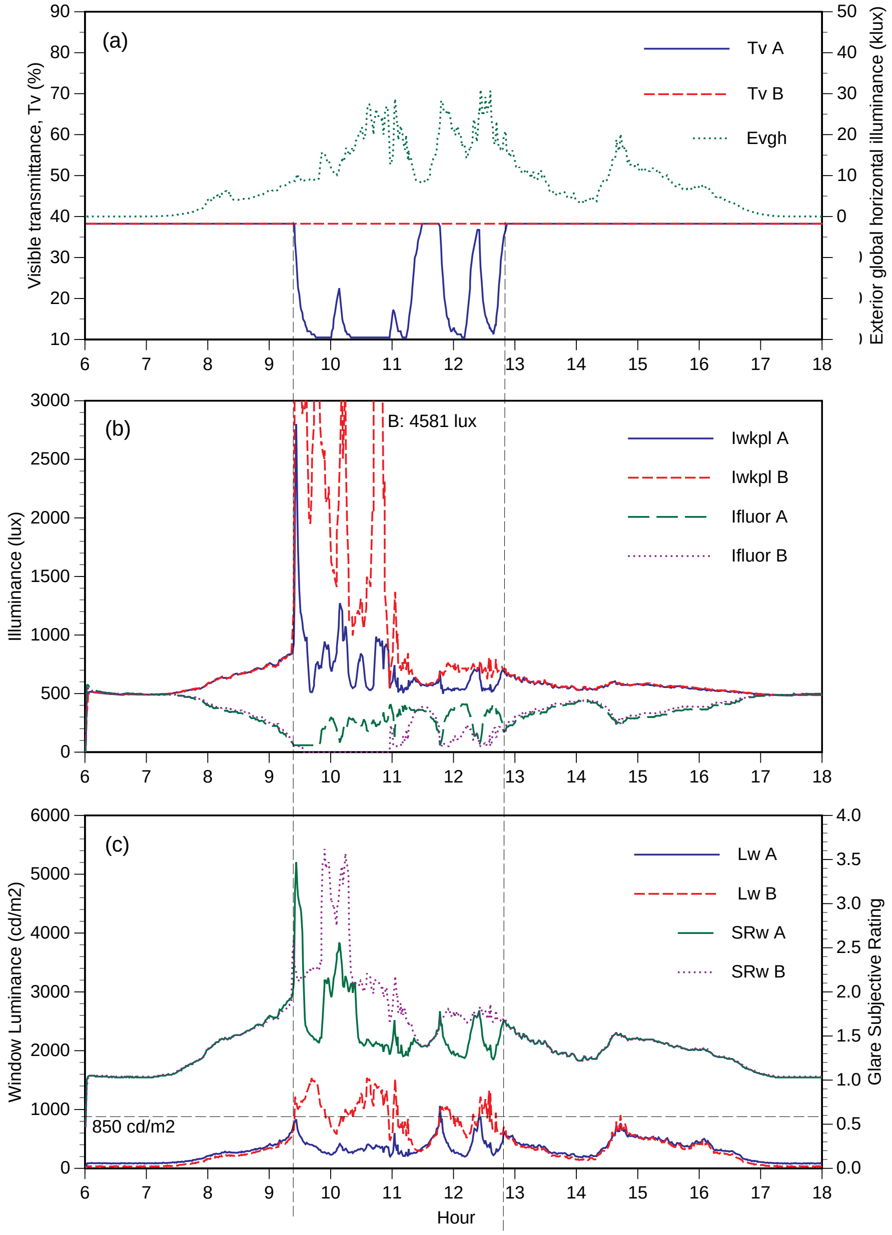

Figure 4. Partly cloudy sky, January 13, 2000
Room A: automated electrochromic; Room B: 38%-glazing

Discussion

Recent advances in materials have resulted in viable large-area electrochromic devices with good performance properties. The electrochromic window system tested had excellent optical clarity, no coating aberrations (holes, dark spots, etc.), uniform density of color across the entire surface during and after switching, smooth gradual transitions when switched, and excellent synchronization or color matching among a group of windows during and after switching. The windows had a very slight yellow tint when fully bleached and a deep Prussian blue when fully colored. The glazings were not reflective. In all outward appearances, the electrochromic windows looked exactly like conventional tinted windows except that the col-

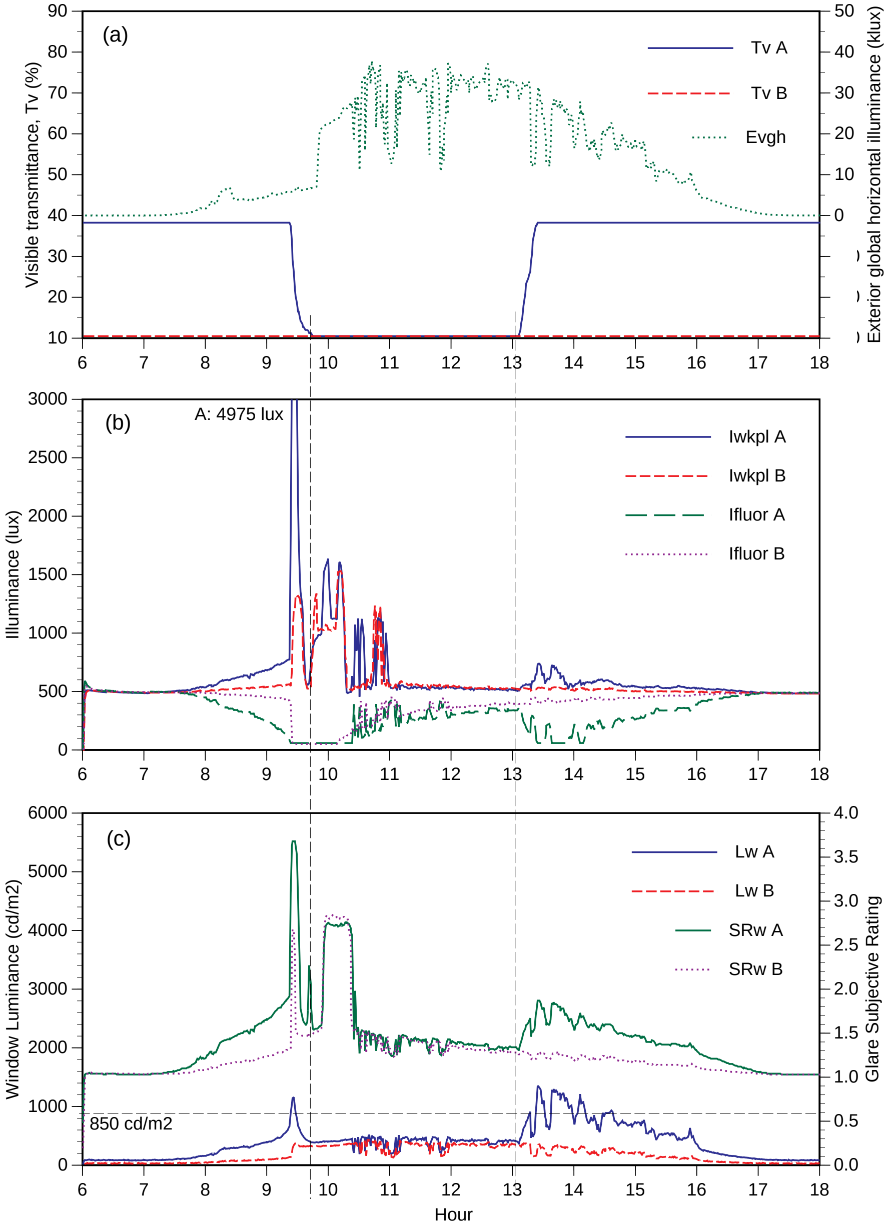

Figure 5. Partly cloudy sky, January 16, 2000
Room A: automated electrochromic; Room B: 11%-glazing

oration could be changed. These windows were large (90x200 cm). Architecturally, the windows imparted a high-tech, spare appearance without the usual intervening window shades.

Daily lighting energy savings were 6 to 24% for overcast to clear sky winter days compared to energy used with the 11%-glazing. Daily lighting energy use was greater (up to 13%) compared with the 38%-glazing. Savings in lighting energy use with daylighting controls occurred simply when the electrochromic transmission was greater than the base case static glazing transmission. On clear sunny days and some partly cloudy days, savings occurred relative to the energy used with the 11%-glazing because there was no direct sun in the early morning and throughout the afternoon; on overcast days, there were energy savings throughout the day.

The transmission range of these electrochromic windows is fairly low (T_v=0.11-0.38).

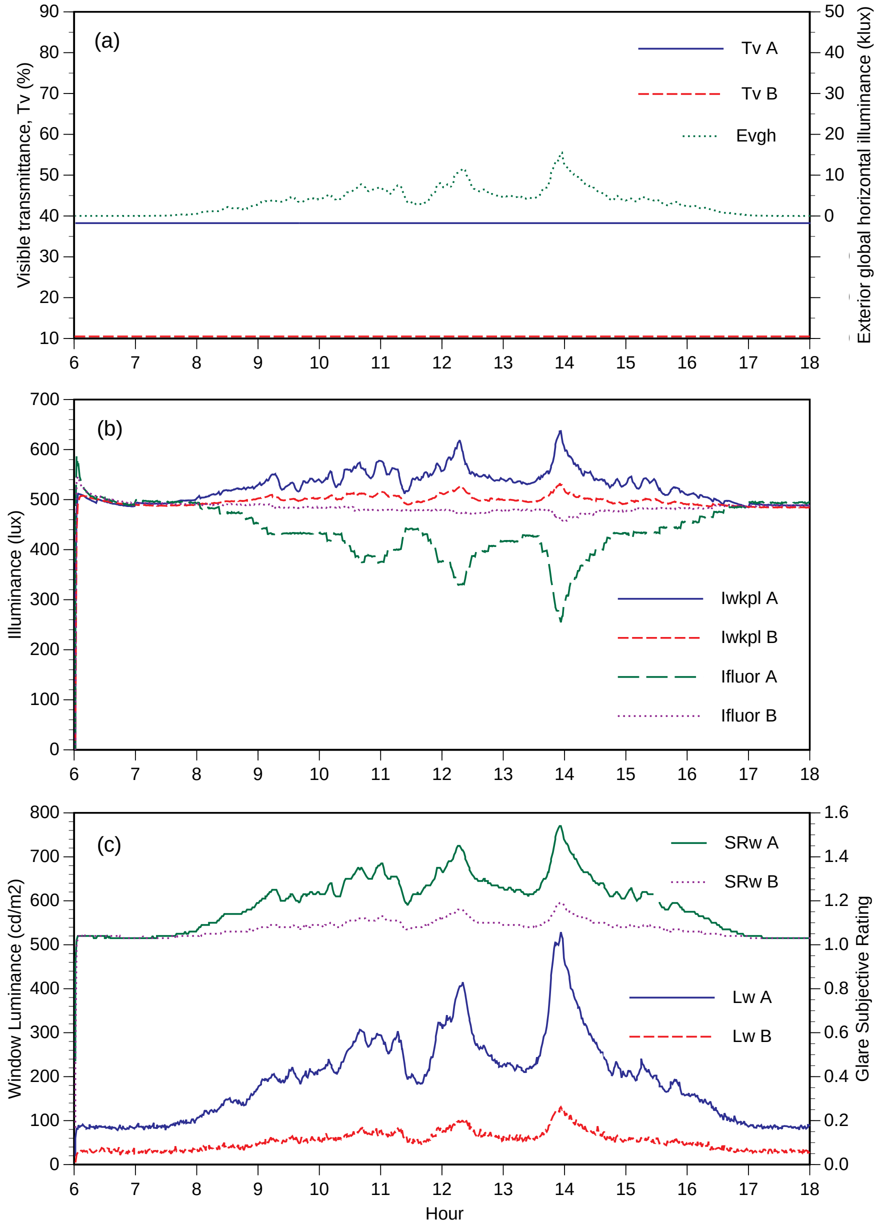

Figure 6. Overcast sky, January 15, 2000
Room A: automated electrochromic (38%); Room B: 11%-glazing

In addition, the electrochromic windows were set to T_v=0.11 when there was direct sun. Both factors contribute to low daylighting potential despite the large window area. Two key tactics can be used to improve lighting energy savings: a) increase the upper T_v limit, and b) relax/ increase the lower T_v limit for direct sun control. For this electrochromic product, the upper T_v limit could have been increased to 51% if it had not been necessary to combine the electrochromic unit with the existing building glazing.

We considered the performance of electrochromic window systems for two types of office tasks. For reading, writing, and object-manipulation-type tasks, the most significant and immediately apparent benefit of electrochromic windows was the simultaneous provision of view and control of interior illuminance. On sunny clear winter days, excessive work plane

Table 1. Daily Lighting Energy Use (Wh)

	Clear Sky	Partly Cloudy	Overcast
Date	12/20/99	1/16/00	1/15/00
E_{vgh} (klux)	13.1	13.2	3.6
EC-glazing (Wh)	2,179	2,181	2,680
11%-glazing (Wh)	2,563	2,606	2,931
Δ (Wh)	384	425	251
Δ%	15.0%	16.3%	8.6%
Date	12/11/99	1/13/00	1/10/00
E_{vgh} (klux)	13.3	8.5	4.3
EC-glazing (Wh)	2,257	2,332	2,640
38%-glazing (Wh)	2,034	2,122	2,738
Δ (Wh)	-223	-210	98
Δ%	-11.0%	-9.9%	3.6%

Evgh=daily average exterior global horizontal illuminance

illuminance from low-angle direct sun could be reduced to 3,500 lux with the electrochromic window at T_v=0.11 compared to 17,185 lux with 38%-glazing. In the afternoon, the electrochromic transmission could be gradually increased as available daylight diminished. Direct sun with controlled intensity can be pleasant in a work space on a winter day. Direct source glare from reflections off a task or surrounding objects can usually be avoided by changing the position of the task or the eye. Throughout the day, an unobstructed view provides ocular relief and relaxation, and connection to the outdoors.

With a computer-based task, visibility and visual comfort requirements are stringent because the task is self illuminating. The intensity of light incident on the computer screen and on opposing room surfaces must be tightly controlled to prevent image washout and veiling reflections. To avoid eye fatigue and discomfort glare, background luminance within the occupant's field of view must also be well controlled. When the winter sun was low and within the view of the occupant or striking the screen directly, sun was inadequately controlled by the electrochromic window even at its lowest state, T_v=0.11. Screen image washout was readily apparent, and glare from direct views of the sun was intolerable. Direct sun control was also not immediate: both large and small electrochromic windows exhibited a relatively slow response time (9 to 26 minutes); unstable sun and sky conditions can fluctuate E_{vgh} by 20-40 klux within 1 to 2 seconds (e.g., Figure 4). For task locations facing the side wall at ~2.5 m from the window, background luminance levels of the side walls could be suitably controlled; however, depending upon the position of the task in the space, direct sun still could cause visibility problems with incident light on the screen, veiling reflections, and striations of bright light across the task. If occupants lack the flexibility to change the task or eye position, interior or exterior shading devices will be required to ensure visual comfort under direct sun.

The electrochromic window does permit more control over background luminance than does the unshaded 38%-glazing base case, so, in this instance, the electrochromic will provide greater visual comfort. Two indices were monitored to allow comparison of discomfort glare

Table 2. Lighting Quality

Date & Sky Condition	Case	Max WPI (lux)	Max Rear WPI (lux)	Rear WPI avg±sd (lux)	Daily Lw avg±sd (cd/m^2)	% of day Lw >850	Glare SR avg±sd	Max SR
12/20/99	EC	8,310	2,946	622± 306	422± 342	12%	NA±NA	NA
Clear	11%	4,802	2,009	599± 260	222± 174	0%	NA±NA	NA
12/11/99	EC	8,110	2,741	609± 291	403± 303	12%	NA±NA	NA
Clear	38%	17,185	8,340	1,903±1,508	815± 681	48%	NA±NA	NA
1/13/00	EC	5239	2801	605± 177	302± 171	0%	1.4± 0.3	3.5
P. Cloudy	38%	15,163	4,581	812± 679	418± 378	16%	1.5± 0.5	3.6
1/16/00	EC	6,780	4,975	627± 376	392± 282	8%	1.4± 0.4	3.7
P. Cloudy	11%	4,143	1,530	563± 174	179± 135	0%	1.3± 0.4	2.8
1/15/00	EC	2,219	637	527± 31	193± 95	0%	1.2± 0.1	1.5
Overcast	11%	751	533	497± 21	53± 21	0%	1.1± 0.0	1.2

Notes: P=Partly, EC=electrochromic, WPI=work plane illuminance, avg=average, sd=standard deviation, L_W=window luminance, SR=subjective rating, NA=not available

for VDT tasks: (1) average window luminance, and (2) discomfort glare subjective rating (SR) facing the window (worst case). Under partly cloudy skies (Figure 4), the 38%-glazing exceeded the “just disturbing” to “just noticeable” borderline (SR>1.5) for 105 minutes longer than the EC-glazing during the day. On a clear day (Figure 2), the window luminance of the 38%-glazing significantly exceeded the IES RP-1 850 cd/m^2 limit with 1,110-1,790 cd/m^2 from 9:00 to 14:00 while the electrochromic window was maintained at ~400 cd/m^2 from 9:30 to 12:30, and no more than 1,080 cd/m^2 throughout the day.

It should be noted that, when the electrochromic window was switched to fully colored to control direct sun and glare, there were adverse effects on daylight illuminance levels, lighting energy savings, and room brightness. The electrochromic cannot simultaneously control direct sun and provide daylight for energy efficiency. Opaque shading systems can satisfy both requirements, but they compromise view. Electrochromic glazings that have a large contrast ratio and high transmission in the bleached state are preferred, e.g., devices that can switch between T_v≈0.06-0.85 will have greater applicability and potentially yield greater energy savings than the device we tested. At this time, some developers have small-area devices with contrast ratios of 11:1 (e.g., T_v=0.07-0.81).

Although no measurements were made to determine thermal comfort, additional shading systems may also be required to ensure the comfort of directly irradiated occupants. This area of research is fairly undeveloped because most comfort models assume that no direct sun strikes the subject. Fanger (1970) conducted some tests on irradiated subjects, and Huizenga et

Table 3. Switching Speed

Command	Day	Hour of day	Lower window speed (min)	Upper window speed (min)	Surface Temperature (°C)
full bleach to full color	12/11/99	9:00	20	12	25-29
	12/20/99	9:15	21	13	26-29
	1/13/00	9:24	21	14	26-29
	1/13/00	11:46	23	12	34-35
	1/16/00	9:22	22	13	25-29
	1/26/00	5:00	25	18	14-15
	1/29/00	5:00	26	15	13-15
full color to full bleach	12/20/99	12:52	15	10	39
	1/13/00	12:39	14	9	32
	1/26/00	6:00	18	10	14-17
	1/29/00	6:00	19	11	13-15

Note: Lower EC window area is 1.073 m^2. Upper EC window area is 0.267 m^2.

al. (1999) plan to continue this work with a multi-node mathematical model. Thermal discomfort can also occur as a result of radiative exchange between the hot window surface and the occupant. The electrochromic glazing layer rejects heat by absorption, rather than reflection, so it can get quite hot when irradiated. Surface temperature calculations using WINDOW4.1 (1994) under ASHRAE Summer Conditions (T_{out}=31.7°C, T_{in}=23.9°C, and Solar=783 W/m^2) of the fully colored dual-pane electrochromic window (without the existing third pane) indicate that the inside glass surface temperature (T_{surf}=23.9°C) may not significantly contribute to thermal discomfort. Low-E coatings on surface two or three will further reduce radiative effects. Some manufacturers may impose surface temperature limits on the electrochromic itself and force "relaxation" or no-switching activity to prevent coating damage if these limits are exceeded.

Switching time of an electrochromic glazing is dependent on materials, size, and temperature, and is exponential (i.e., it achieves ~50% of the total change in coloration within ~25% of the total time to switch). The larger lower windows switched more slowly (14 to 26 min) than the smaller upper windows (9 to 18 min) at surface temperatures of 35˚C to 13°C, and all switched faster from colored to bleached than bleached to colored ($\Delta t \approx 6$ min) (see Table 3 above). This response time is inadequate for light-critical tasks requiring immediate control, particularly in cold climates. For a given electrochromic device, switching speed can be improved by using smaller window units, decreasing the distance between bus bars, or reducing the resistivity of the transparent electrical conductor. Materials scientists may consider the second design option, in which electrical wires are run within the transparent region of the glass (as in car window defoggers). Development of alternative, cost-effective transparent conductors will likely take place in the field of computer displays.

Cycling, or the repeated charging and discharging of an electrochromic device, defines the sustained performance or lifetime of the window. Durability tests are being performed for 25,000 to 50,000 cycles, assuming an average of three to five cycles per day for 20 to 30 years (Czanderna et al. 1999). Pause times, depth of cycling (degree of coloration), and frequency of cycles all affect the longevity of the device. Our results suggest that the number of cycles will be more than two per day if partly cloudy skies are dominant in a climate and if the window is switched for reasons other than illuminance control.

The manufacturer provided a simple, manual user interface that gave useful feedback, with five separate diodes for each level of switching and status indicators (blinking lights when in the process of switching; continuous lights when no activity). The user interface is designed to be hard wired to a master controller box serving a series of single-pane electronic controllers, which are connected via snap-together flat cables to individual window units. The manual user interface was not used in these tests. Instead, an interface to the manufacturer's master controller was built and integrated with the electric lighting system to automate control of both the windows and lighting systems. Automated control software and integrated control with other subsystems (lighting, HVAC, etc.) are not currently offered by electrochromic manufacturers.

Several constraints were imposed on this integrated control system: 1) photosensor calibrations had to account for the highly variable direct sun luminance distributions in the room, and 2) integrated control had to accommodate the design limitations of the electrochromic device noted below. For most photosensor applications, direct sun is assumed to be controlled or not present in the room because correlations to work plane illuminance are significantly more non-linear with the presence of direct sun. This limitation makes it difficult to accurately calibrate the photoelectric system. Very conservative correlations were used in this test to ensure that illuminances were maintained at the design level. This approach reduced lighting energy savings. The electrochromic controller itself has fairly fussy requirements to prevent inadvertent permanent damage, improve durability, and increase lifetime of the device. These requirements can adversely affect switching speeds.

To improve overall performance and user satisfaction, we expect electrochromic windows to be controlled by both the user and an automated system. An automated system cannot fully accommodate occupant preferences for illuminating a given task type, position, and field of view as well as addressing conditions and concerns including glare, direct sun, privacy, view, brightness, color rendition, and a multitude of others. Energy-efficiency algorithms are best implemented with permission of the occupant and may require that the occupant relinquish some autonomy regarding the system during critical peak energy use periods. For public (lobbies, glazed hallways, cafeterias, etc.) or open-plan shared spaces, some lack of autonomy regarding the window system may be acceptable to occupants. Multi-pane windows will allow more flexible control than a single-opening window. In this test, the upper windows could be controlled separately from the lower windows, enabling daylight admission through the upper aperture and glare and direct sun control through the lower. Lateral control of individual windows may also be useful because glare sources can shift spatially across a portion of the horizontal view.

It is pertinent to briefly discuss the "realistic" baseline window system that is now being used in commercial buildings. In the U.S., particularly in new commercial buildings, low-transmission glass is used to meet energy codes in most states (for cooling load control), and interior shades are used to control direct sun and glare. The flush facade predominates; overhangs and fins are atypical. Spectrally-selective low-E glazing has improved daylighting efficacy while providing thermal control that is equivalent to or better than that offered by its conventional absorptive low-E-glazing cousin. However, interior shading systems often reduce daylighting benefits because they are seldom "optimally" controlled. The net result is that, in order to achieve both an energy-efficient and comfortable interior environment, one must rely on luck and the good graces of occupants to actively and properly manage windows. Anecdotal observations show that windows in real buildings are seldom well managed. Hence, we believe that increased energy efficiency and improved visual comfort can be obtained with electrochromic windows.

There are few real-world installations of electrochromics from which the architectural community can learn. In 2000, a four-story ~9x22-m array of large-area electrochromic windows will be demonstrated in the lobby of the Stadtsparkasse Bank in Dresden, Germany, and other installations are planned elsewhere. A number of practical issues are related to the specification and installation of electrochromic windows; our demonstration in Oakland provides useful observations regarding some of these issues. The window system we used required special installation procedures. As with all insulating-glass units, sizes had to be specified exactly and cannot be altered at the job site. The window frames had to be carefully designed to protect the edges of the electrochromic device and permit thermal movement. Electronic cabling had to be run through the frames and not be crimped or severed by long-term (e.g., thermal) movement. Access to wiring is useful to troubleshoot failures in the system. Transformers are required to reduce building power down to voltages of 0-5 V. Manual controllers can be mounted on walls adjacent windows. Virtual instrument control panels will be more viable for individual or building-wide control, such as have been implemented for other building systems (e.g., lighting). The color of the window may pose problems for tasks that require accurate color rendition (e.g., in retail and medical buildings, food markets, museums, etc.). Occupants will also be likely to notice the strong blue color if bleached and colored electrochromics are juxtaposed in the same window wall, as was the case in this installation. This contrast may influence their perception of brightness in the space. Separately, the view out is enhanced, particularly sky and clouds. Architecturally, a uniform appearance to the exterior façade should not be expected when electrochromics are used.

Conclusions

The time is approaching quickly when commercial electrochromic window products will appear on the market. This study provides preliminary data on the first full-scale demonstration of large-area electrochromic windows in an office-like setting in the United States. Lighting, illuminance, and control operations data indicate that electrochromic windows can provide greater energy efficiency and improve environmental quality compared to the performance of conventional window systems (glass + shading) in actual buildings. There is considerable room for improvement of either the electrochromic material or the control system to increase switching speed, particularly for use of this technology in cold climates. A detailed, accurate thermal evaluation is required to determine cooling load benefits. Studies to systematically evaluate human factors—subjective response, brightness perception, color perception, and visual and thermal comfort—will be essential.

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